

CPT and Lorentz symmetry tests with entangled neutral kaons at KLOE/KLOE-2

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Abstract. The KLOE experiment at the DAΦNE ϕ -factory located at the INFN Laboratory in Frascati, Italy collected data corresponding to 2.5 fb^{-1} of integrated luminosity. Neutral kaon pairs produced in ϕ -meson decays offer a unique possibility to perform tests of fundamental discrete symmetries. The entanglement of the two kaons is exploited to search for possible violation of CPT symmetry and Lorentz invariance in the context of the Standard-Model Extension (SME) framework. A new approach to the analysis of $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^-, \pi^+ \pi^-$ events has been adopted allowing us to independently measure all four CPT violating parameters Δa_μ appearing for neutral kaons in the SME. The final KLOE results on Δa_μ will be presented. These are presently the most precise measurements in the quark sector of the SME.

1. Introduction

The invariance under CPT operation, the combined action of charge conjugation (C), parity reflection (P), and time-reversal (T), is fundamental in the framework of any quantum field theory. CPT is also one of the best tested symmetries having passed very stringent and diverse experimental tests (eg. $|m_{K^0} - m_{\bar{K}^0}|/m_{av} < 6 \times 10^{-19}$ [1]). As a consequence of Lorentz invariance, unitarity and locality of quantum field theory CPT may be however violated in the presence of quantum gravity effects (QG). In several QG models CPT can be violated via some mechanism which violates also standard Quantum Mechanics (QM) [2, 3], eg. causing decoherence of an entangled quantum state. As a consequence the quantum mechanical operator generating CPT transformations cannot be consistently defined [4]. CPT symmetry may be violated also through spontaneous breaking of Lorentz symmetry [5, 6] or locality [7] of interactions. In these cases the well-defined generator of the CPT symmetry does not commute with the effective Hamiltonian of the system [2]. On phenomenological grounds the CPT and Lorentz symmetries violation induced by quantum gravity effects is expected at energies of the order of $\sim 10^{20} \text{ GeV}$, however they might give rise to observable effects also in the low energy regime, particularly in the entangled neutral meson systems [8]. These effects have been searched for in the B mesons system by the BaBar collaboration [9] and in the neutral kaon system by the KLOE experiment operating at the DAΦNE ϕ -factory. KLOE has provided the world's best upper limits for phenomenological parameters describing CPT violation by decoherence of entangled neutral kaons [10] and by violation of the Lorentz symmetry [11] occurring within the framework of Standard Model Extension (SME) as it will be discussed in this article.



2. Test of CPT and Lorentz symmetries with the KLOE detector

The KLOE experiment [12, 13, 14] operates at the DAΦNE e^+e^- collider working at a center of mass energy of about 1020 MeV. Positron and electron beams collide at an angle of π -25 mrad, producing ϕ mesons with non-zero momentum in the horizontal plane, $|p_\phi| \sim 15$ MeV, in the KLOE reference frame [11].

Neutral kaons from ϕ meson decays are produced in a coherent quantum state:

$$|i\rangle = N (|K_S, \vec{p}_1\rangle |K_L, \vec{p}_2\rangle - |K_L, \vec{p}_1\rangle |K_S, \vec{p}_2\rangle) , \quad (1)$$

where \vec{p}_1 and \vec{p}_2 denote the kaon momenta and N is a normalization factor expressed in terms of the CP impurities ϵ_S and ϵ_L : $N = \sqrt{(1 + |\epsilon_S|^2)(1 + |\epsilon_L|^2)}/2(1 - \epsilon_S\epsilon_L)$. Due to the quantum entanglement of the two neutral kaons their decays are correlated. Thus, the kaons double differential rate of decay into two final states f_1 and f_2 contains a characteristic time interference term [15]:

$$I(f_1, f_2, \Delta t) \sim |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1|^2 |\eta_2|^2 e^{-\frac{(\Gamma_L + \Gamma_S)}{2} \Delta t} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \quad (2)$$

where Δt denotes the proper decay times difference and η_1 and η_2 are the following decay amplitude ratios: $\eta_i = |\eta_i| e^{i\phi_i} = \frac{\langle f_i | T | K_L \rangle}{\langle f_i | T | K_S \rangle}$. Γ_L and Γ_S denote the widths of K_L and K_S meson, respectively. The decay intensities of entangled kaons appear to be very sensitive to any CPT violating effect at the level of the interesting Planck scale region, presently unreachable in other similar systems [15]. If both kaons decay to the same final state (e.g. $\pi^+\pi^-$) the interference pattern in Eq. 2 is very sensitive to any deviation from unity of the ratio η_1/η_2 in the interference region of $\Delta t \approx 0$. These deviations may be present due to the CPT violation which in the framework of SME manifests to lowest order only in the CPT violating parameter δ_K equal to: $\delta_K = (\epsilon_S - \epsilon_L)/2$. This parameter exhibits a dependence on the 4-momentum of the kaon:

$$\delta_K \approx i \sin \phi_{SW} e^{i\phi_{SW}} \gamma_K (\delta a_0 - \vec{\beta}_K \cdot \Delta \vec{a}) / \Delta m , \quad (3)$$

where ϕ_{SW} is the superweak phase, γ_K and $\vec{\beta}_K$ are the boost factor and velocity of kaon and Δm denotes the difference between K_L and K_S mass. The four Δa_μ parameters are a measure of the Lorentz symmetry violation. Neglecting higher order contributions to CP violation the two η parameters can be written as:

$$\begin{aligned} \eta_1 &\cong \epsilon_K - \delta_K(\vec{p}_1, t_s) \\ \eta_2 &\cong \epsilon_K - \delta_K(\vec{p}_2, t_s) , \end{aligned} \quad (4)$$

where $\epsilon_K = (\epsilon_S + \epsilon_L)/2$. Since the Earth is rotating the CPT and Lorentz violating parameters are usually considered in the fixed stars reference frame which makes δ_K dependent also on the sidereal time t_s after the transformation from the laboratory frame [15].

At KLOE a search for the Lorentz and CPT symmetries violation have been performed by measurements of the interference pattern for both kaons decaying to $\pi^+\pi^-$ final states. A sample of 1.7 fb^{-1} of integrated luminosity gathered in the 2004-2005 data taking period have been used in this analysis. Moreover, we have generated two Monte Carlo samples: one contains all the ϕ meson decay channels (used for analysis optimization); the other is a MC signal sample which have been used for efficiency and decay time difference resolution determination. The first preselection of data was done requiring two vertices with two tracks of opposite curvature. Assuming the pion hypothesis for every track we have then applied a set of kinematical cuts [11]:

- $|m_{\text{trk}} - m_K| < 5 \text{ MeV}/c^2$, where m_K denotes the kaon mass and m_{trk} is the invariant mass of the kaon reconstructed from the tracks assuming charged pion mass hypothesis: $\vec{p}_{1(2)} = \vec{p}_{\pi_{1(2)}^+} + \vec{p}_{\pi_{1(2)}^-}$ and $E_{1(2)} = E_{\pi_{1(2)}^+} + E_{\pi_{1(2)}^-}$.

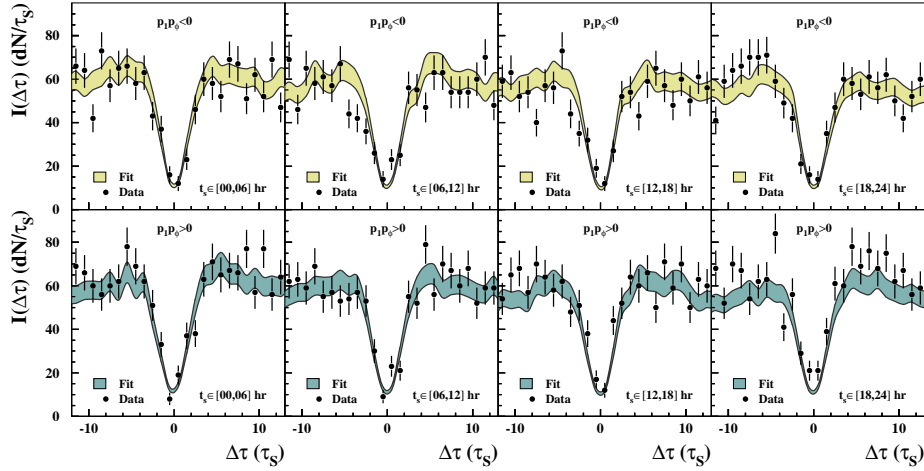


Figure 1. Distributions of the double differential decay rates into $\pi^+\pi^-$, $\pi^+\pi^-$ final states measured with the KLOE detector. The top panel contains distributions for four bins of sidereal time when kaon emitted in the forward hemisphere ($\cos\theta > 0$) in the KLOE reference frame was moving along with the ϕ momentum (i.e. $\vec{p}_{1(2)} \cdot \vec{p}_\phi > 0$). The lower panel shows distributions for a subset of data where kaon emitted in the forward hemisphere was moving in the opposite direction (i.e. $\vec{p}_{1(2)} \cdot \vec{p}_\phi < 0$). The results of the fit is indicated together with uncertainties by colored bands (figure taken from [11].)

- $\sqrt{E_{\text{miss}}^2 + |\vec{p}_{\text{miss}}|^2} < 10 \text{ MeV}$, where $\vec{p}_{\text{miss}} = \vec{p}_\phi - \vec{p}_1 - \vec{p}_2$ and $E_{\text{miss}} = E_\phi - E_1 - E_2$;
- $-50 \text{ MeV}^2/c^4 < m_{\text{miss}}^2 < 10 \text{ MeV}^2/c^4$, where $m_{\text{miss}}^2 = E_{\text{miss}}^2 - |\vec{p}_{\text{miss}}|^2$
- $|p_{1(2)}^* - p_0^*| < 10 \text{ MeV}/c$, where $p_{1(2)}^*$ is the momentum of the kaon, as derived from tracks, in the ϕ meson reference frame, while $p_0^* = \sqrt{s/4 - m_K^2}$ and \sqrt{s} is the center-of-mass energy.

According to MC simulations the remaining data sample contains a small fraction of irreducible background mainly due to kaon regeneration in the thin beryllium cylindrical foil inside the interaction region ($\sim 2\%$) and due to the $e^+e^- \rightarrow 4\pi$ reaction. In order to improve the accuracy of decay time measurements a dedicated global fit procedure has been performed [11]. Since the resolution of decay time difference deteriorates at large pion opening angles θ_π we have rejected all events with $\cos\theta_\pi < 0.975$.

The data sample was divided into two subsets: one containing events where kaon emitted in the forward hemisphere ($\cos\theta > 0$) in the KLOE reference frame was moving along with the ϕ momentum (i.e. $\vec{p}_{1(2)} \cdot \vec{p}_\phi > 0$), and the second one with events where kaon emitted in the forward hemisphere was moving in the opposite direction (i.e. $\vec{p}_{1(2)} \cdot \vec{p}_\phi < 0$). Moreover, the dataset was divided into four bins of sidereal time. For every subset of data the decay intensity distribution as a function of Δt was determined. The distributions were fitted simultaneously with the interference pattern taken from Eq. 2 and assuming possible modulation effects induced by the CPT-violating parameter δ_K as in Eq. 3. The resulting eight distributions are presented in Fig. 1, where the difference of decay times Δt is expressed in the units of K_S lifetime. The colored bands represent the fit uncertainty due to finite MC simulation statistics and efficiency correction.

The values of Δa_μ parameters determined from the fit are:

$$\begin{aligned}\Delta a_0 &= (-6.0 \pm 7.7_{\text{stat}} \pm 3.1_{\text{syst}}) \times 10^{-18} \text{ GeV}, \\ \Delta a_x &= (0.9 \pm 1.5_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-18} \text{ GeV},\end{aligned}$$

$$\begin{aligned}\Delta a_y &= (-2.0 \pm 1.5_{stat} \pm 0.5_{syst}) \times 10^{-18} \text{ GeV}, \\ \Delta a_z &= (3.1 \pm 1.7_{stat} \pm 0.5_{syst}) \times 10^{-18} \text{ GeV}.\end{aligned}$$

These results do not reveal any CPT or Lorentz symmetries violation and constitute first measurement of these quantities in the kaon sector. The detailed description of the systematic uncertainties can be found in [11].

3. Future prospects

The CPT and Lorentz symmetries violation are one of the main physics topics of the KLOE-2 experiment which is continuing and extending the physics program of its predecessor [16]. For the forthcoming run the KLOE performance have been improved by adding new subdetector systems: the tagger system for the $\gamma\gamma$ physics, the Inner Tracker based on the Cylindrical GEM technology and two calorimeters in the final focusing region [17]. The new inner detector will increase the tracking and vertexing capabilities of KLOE allowing for significant reduction of systematic uncertainties which together with the higher statistics expected by KLOE-2 will significantly improve the present result.

Acknowledgments

This work was supported in part by the EU Integrated Infrastructure Initiative Hadron Physics Project under contract number RII3-CT- 2004-506078; by the European Commission under the 7th Framework Programme through the ‘Research Infrastructures’ action of the ‘Capacities’ Programme, Call: FP7-INFRASTRUCTURES-2008-1, Grant Agreement No. 227431; by the Polish National Science Centre through the Grants No. DEC-2011/03/N/ST2/02641, 2011/01/D/ST2/00748, 2011/03/N/ST2/02652, 2013/08/M/ST2/00323, 2013/11/B/ST2/04245, and by the Foundation for Polish Science through the MPD programme and the project HOMING PLUS BIS/2011-4/3.

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